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ADVANCED CONCEPTS TO INCREASE TURBINE BLADE LOADING

by Warner L. Stewart and Arthur J. Glassman
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Winter Annual Meeting and Energy Conversion Exposition sponsored by the American Society of Mechanical Engineers
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ABSTRACT

Blade loading is examined in terms of surface diffusion and loading effectiveness parameters. These parameters serve to define the level of loading, with higher values of each representing higher loading on the blade. Advanced blading concepts designed for efficient utilization of high values for each of these factors are discussed. Experimental results demonstrating these design concepts are presented.

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INTRODUCTION

The design of a turbine involves a balance between efficiency and size and/or weight. Reductions in diameter, number of stages, or number of blades all result in smaller and/or lighter turbines. These reductions, however, are accompanied by decreasing values of reaction and/or solidity, both of which result in a requirement for more work per blade. As the loading per blade is increased, the flow on the blade surfaces is characterized by increased decelerations. It is these decelerations, which are associated with increased profile loss and eventual separation of the boundary layer, that impose limitations on the amount of loading that can be used.

If increased blade loadings are to be utilized in advanced turbine designs, then these high loadings must be obtained without the previously mentioned high losses. Some factors useful for representing blade loading were presented in [1]. These were a surface diffusion parameter and a loading coefficient. Similar factors have been used previously to correlate blade loss (e.g., [2]).

The purpose of this paper is to examine means for obtaining increased loading in terms of these diffusion and loading factors. Advanced blading concepts designed for efficient utilization of each of these factors are described, and experimental results demonstrating the design concepts are presented.

SYMBOLS

c_x	axial chord
D_s	suction surface diffusion parameter, Equation (3)
p	static pressure
R	reaction, Equation (5)
s	spacing
V	velocity
$\Delta\beta$	turning angle, deg
ρ	mass density
σ_x	axial solidity, c_x/s
ψ	loading effectiveness
ψ_Z	Zweifel loading coefficient

Subscripts

max	maximum
min	minimum
s	suction surface
u	tangential
x	axial
1	inlet
2	outlet

Superscript

'	total

LOADING FACTORS

Blade loading can be related to blade solidity and reaction by means of a coefficient relating actual to ideal loading. A typical blade row with the asso-

ciated surface velocity distribution (loading diagram) and nomenclature is shown in Fig. 1. In this paper, the ideal loading force is defined by the static pressures being constant at the inlet total pressure on the pressure surface and at the minimum static pressure on the suction surface. Using this definition, a loading effectiveness is defined as

$$\psi = \frac{\rho V_x s \, \Delta V_u}{(p_1' - p_{s,\,min}) c_x} \tag{1}$$

This loading effectiveness differs from the loading coefficient presented in [1] in the definition of the ideal constant pressure on the pressure surface. Since the static pressure at the stagnation point is theoretically the inlet total pressure, it is used here to represent the ideal value on the pressure surface.

The loading effectiveness also differs from the well-known Zweifel loading coefficient [3], which is based on an ideal suction-surface static pressure equal to the exit static pressure. Thus, the value of Zweifel's coefficient can exceed unity in cases where high suction-surface diffusions are encountered. The loading effectiveness, which is based on an ideal suction-surface static pressure equal to the minimum pressure on that surface, is limited to a maximum value of unity. These two loading factors are related as

$$\frac{\psi_Z}{\psi} = \frac{p_1' - p_{s,\,min}}{p_1' - p_2} \tag{2}$$

For incompressible flow with no loss, and using the suction-surface diffusion parameter defined in [1] as

$$D_s \equiv \frac{V_{max}^2}{V_2^2} \tag{3}$$

Equation (2) becomes

$$\frac{\psi_Z}{\psi} = D_s \tag{4}$$

Equation (1) can be transformed into the desired interrelationship among the factors affecting blade loading by assuming incompressible flow with no loss, using the suction-surface diffusion parameter definition of Equation (3), and the definition of reaction, which is

$$R \equiv 1 - \frac{V_1^2}{V_2^2} \tag{5}$$

Making these substitutions in Equation (1) and solving for solidity ($\sigma_x = c_x/s$) yields

$$\sigma_x = \left(\frac{1}{\psi}\right)\left(\frac{1}{D_s}\right) 2\sqrt{1 - R}\,\sin\Delta\beta \tag{6}$$

Equation (6) indicates that for given velocity-diagram requirements (constant R and $\Delta\beta$), lower solidity can be obtained if increased loading effectiveness and/or suction surface diffusion can be achieved. Also indicated by Equation (6) is an increase in solidity with decreasing reaction. To offset this consequence of lowering reaction, higher values of diffusion and/or effectiveness are again desired. The increase in blade loading, as represented by higher values of suction surface diffusion and/or loading effectiveness, however, must be accomplished without greatly increasing the flow losses. Increasing suction surface diffusion is known to result eventually in flow separation and associated severe losses. Methods must be found, therefore, to utilize high diffusion without high losses or to eliminate the diffusion from the suction surface and thus increase loading effectiveness by maintaining a high

loading over the length of the blade.

ADVANCED CONCEPTS

In accordance with the previous discussion, advanced concepts for maintaining high diffusion without excessive loss and also for increasing the loading effectiveness while eliminating high diffusion from the blade suction surface are currently the subject of both in-house and contract [4, 5] studies. The concepts being studied are the tandem blade, jet flap, tangential jet, and vortex generators. To illustrate concepts designed for high diffusion and high effectiveness, the tandem blade and jet flap will be discussed in this paper.

The tandem blade concept, shown in Fig. 2(a), is designed to utilize high diffusion without separation. The slot between the two airfoils serves to break and reenergize the thickening boundary layer, and thus retard separation. The jet flap concept, shown in Fig. 2(b), is designed to alter the velocity distribution by using a secondary jet of air to eliminate high diffusion on the suction surface and increase loading effectiveness.

Tandem Blade

A photograph of the tandem blade rotor being studied as part of the program discussed in [4] is shown in Fig. 3. The mean section of a slightly modified version of this blade row was the subject of a cascade study by Nosek of Lewis Research Center. A velocity distribution obtained from these cascade tests is shown in Fig. 4. It can be seen that high suction-surface diffusions were obtained, especially on the rear airfoil. The exit survey of total pressure for the data shown in Fig. 4 is presented in Fig. 5. The flow did not separate from the suction surface of the rear airfoil despite the high diffusion that existed. This was evident from the shape of the exit survey trace and

other associated data and calculations. It can be noted that the wake from the front airfoil still exists to some extent at the blade-row exit.

Jet-Flap Blade

A photograph of an annular cascade sector containing jet-flap blades is shown in Fig. 6. The blades are representative of a highly-loaded stator and are being tested in the program discussed in [5]. Experimental velocity distributions obtained from the cascade tests are presented in Fig. 7 for the cases of no jet flow and 4 percent jet flow. It is seen that the use of jet flow eliminates the diffusion on the suction surface, thus increasing the loading in the exit region of the blade. In this manner, the loading effectiveness is increased.

Since secondary air must be used for the jet-flap concept, the gains in loading must be weighed against any penalties associated with the use of the secondary air. In a case where the blades must be cooled, the secondary air is already available within the blade and opportunity exists for using the same air for both cooling and increasing blade loading.

CONCLUDING REMARKS

Means for obtaining the increased blade loadings desired for advanced applications were examined in terms of surface diffusion and loading effectiveness factors. The surface diffusion term represents the velocity deceleration on the blade suction surface. The loading effectiveness represents the loading that is actually achieved as a fraction of the ideal loading defined by the suction surface maximum velocity. Increases in the value of each of these parameters can result in increased blade loadings.

Advanced concepts for obtaining high diffusion without excessive loss and also for eliminating high diffusion from the blade surface while increasing

loading effectiveness are currently being investigated. A concept designed to utilize high diffusion without separation is the tandem blade, while the jet-flap blade is a concept designed to eliminate high suction surface diffusion on the blade while yielding a high loading effectiveness. Experimental results thus far obtained have served to encourage further work in these areas.

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5. J. L. Bettner, "Experimental Investigation in an Annular Cascade Sector of Highly Loaded Turbine Stator Blading. I. Analysis and Design," General Motors Allison Div. Report EDR 5315, 1968.

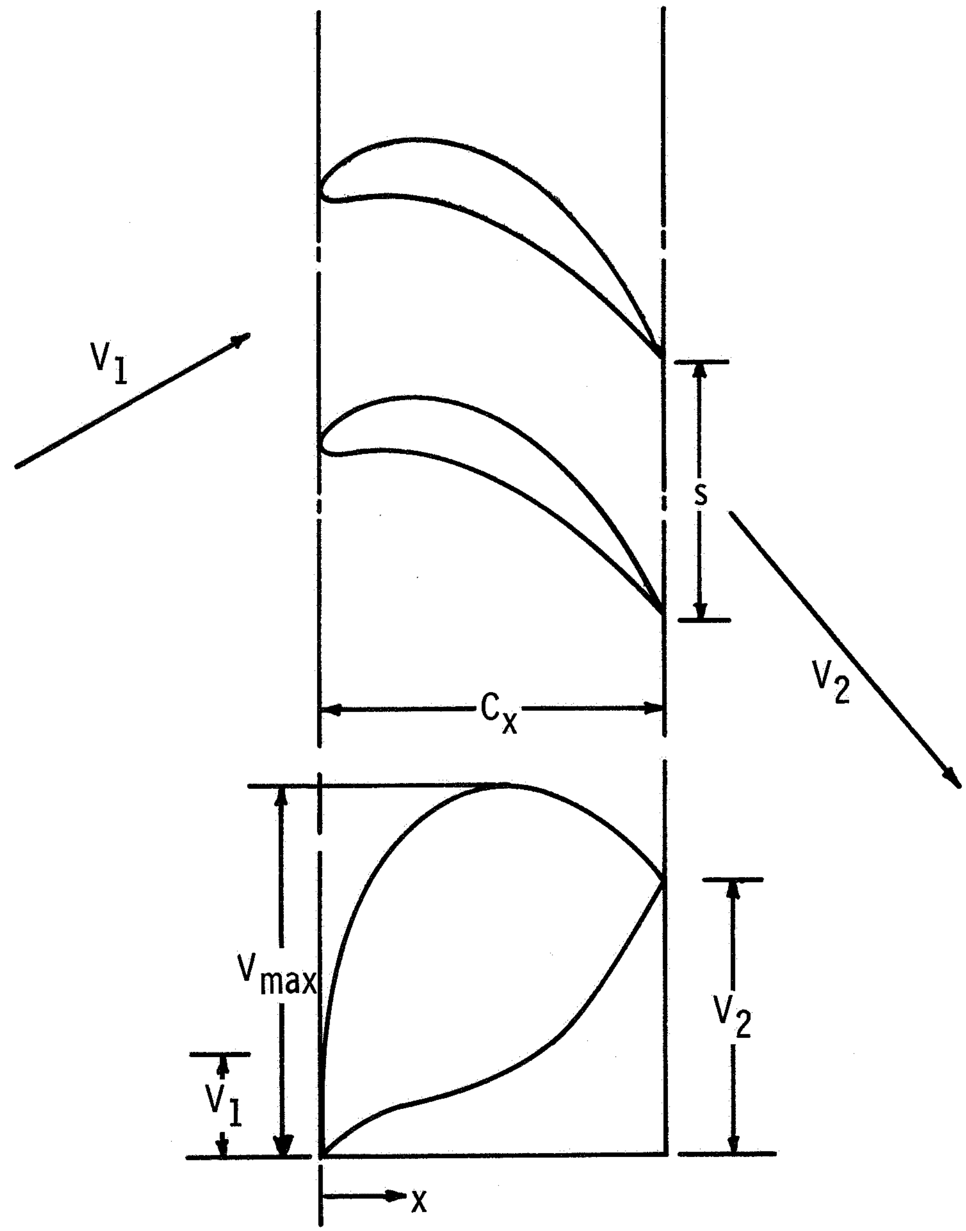
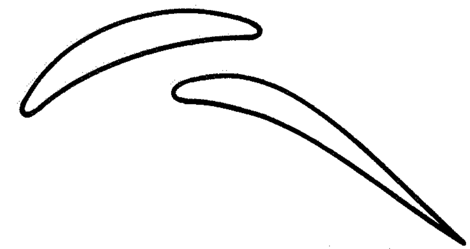
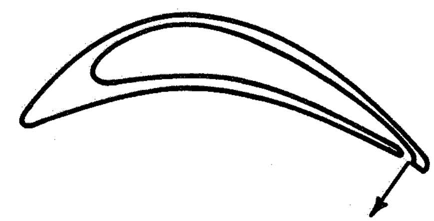


Figure 1. - Typical blade row with surface velocity distribution.



(a) Tandem blade.



(b) Jet flap.

Figure 2. - Increased blade loading concepts.

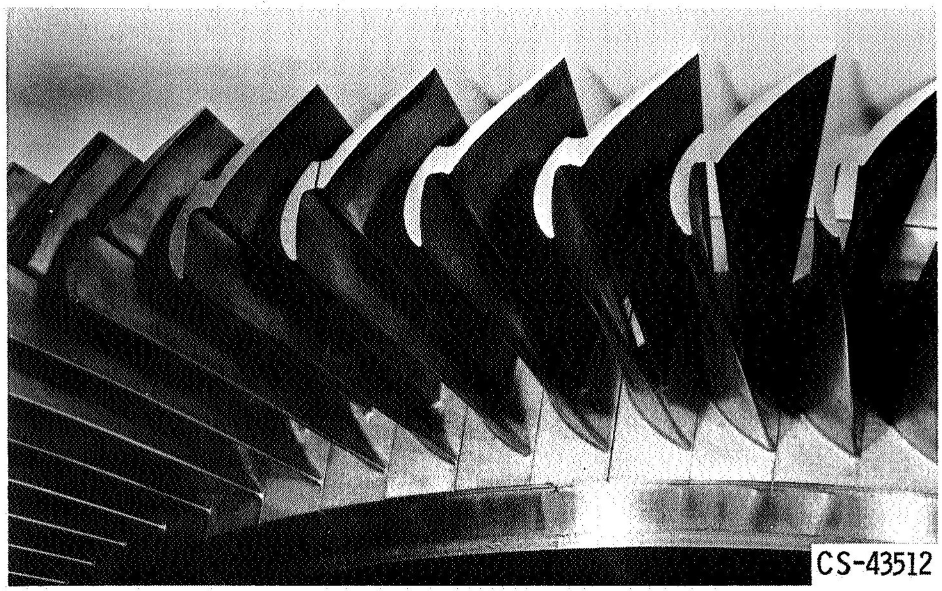


Figure 3. - Tandem blade rotor.

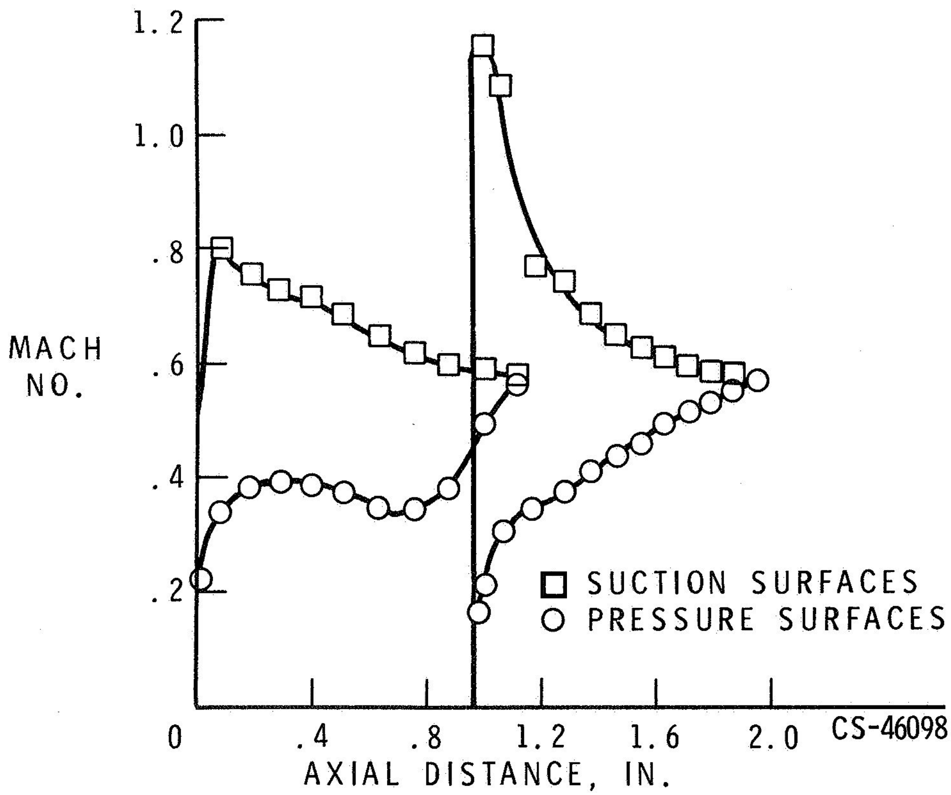


Figure 4. - Tandem blade experimental velocity distribution.

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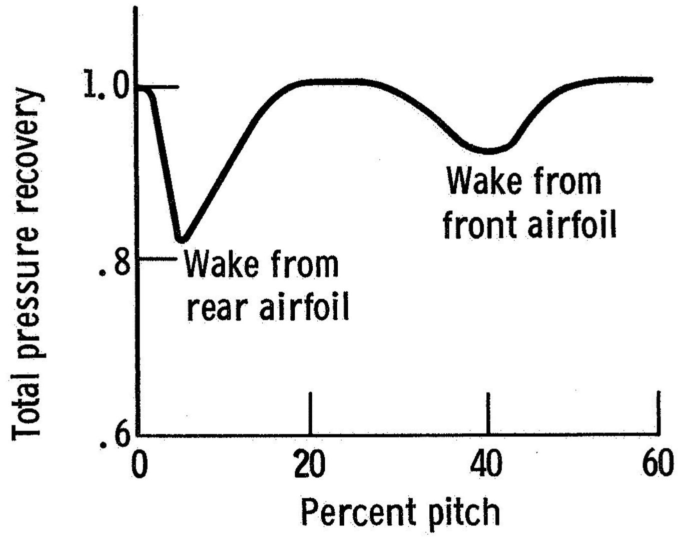

Figure 5. - Tandem blade survey data.

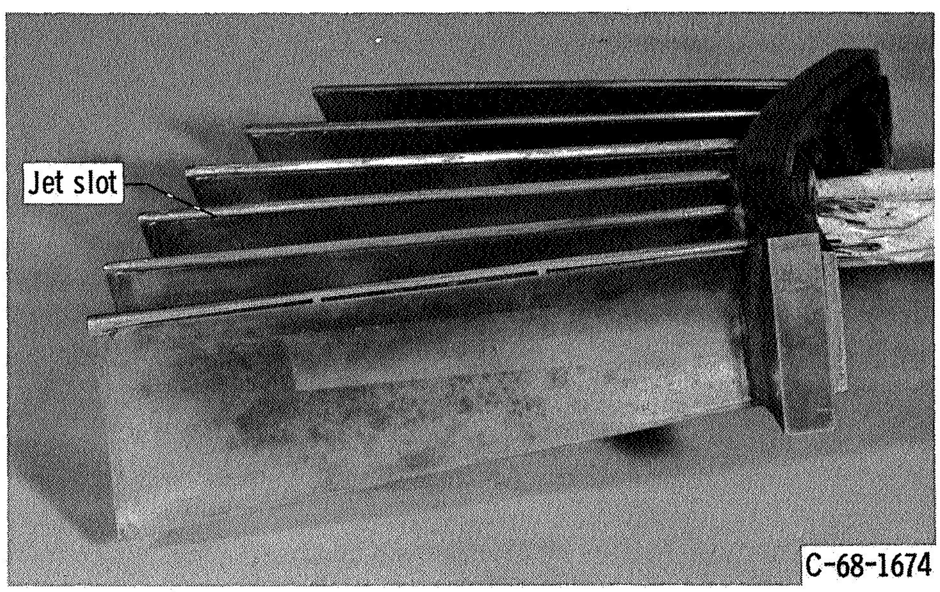

Figure 6. - Jet-flap blade annular cascade.

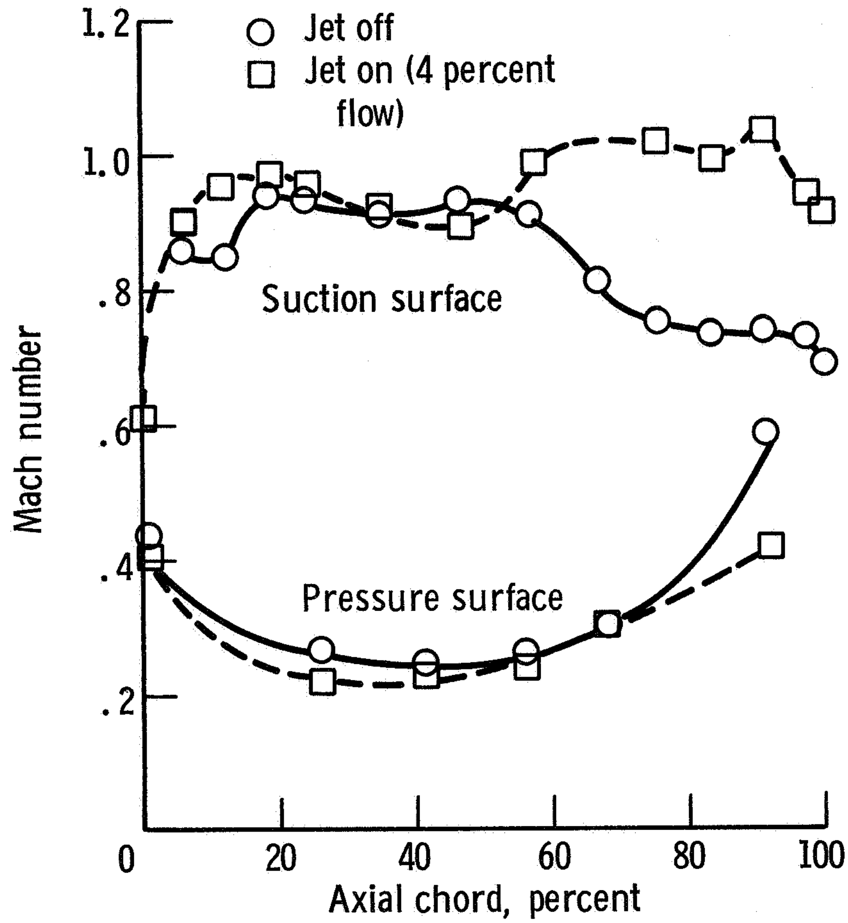

Figure 7. - Jet flap experimental velocity distributions.